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Influence of architectural building envelope characteristics on energy performance in Central European climatic conditions

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ABSTRACT

During early building design stages, decisions are made regarding building's form, orientation, distribution, and size of glazing. Although these features are crucial for building energy performance, designers rarely base their decisions on elaborate energy simulations. The paper presents a study of the interconnectedness of building form, orientation and window area in regard to energy consumption for heating and cooling of a generic building in Central European climate. The study showed that for the considered climate, an elongated building form is more suitable than the compact one, because it allows larger window areas and thus more efficient solar energy harvesting. Even though this may be advantageous for the heating period, it represents a potential problem during the cooling season. Therefore, appropriate shading must be applied and thus the optimum solution is achieved in regard to the building's cumulative yearly energy consumption.

1. Introduction

In the near future low use of energy in buildings is going to become a reality required by stringent EU regulations – nZEB goal [11,12] and imposed by environmental aspects [26]. It is generally considered that the most significant influence on the final energy performance of buildings can be attained during the early stages of building design [10]. Because the majority of Europe has predominantly moderate to cool climate [24], designers tend to choose building features that reduce heat losses. At the same time, the influence of heat gains on the overall energy consumption is often underestimated ([13,41]). The same goes for legislation, which is in EU mainly focused on heating energy consumption of buildings and does not encourage designers to search for optimised and integrated solutions [25]. This situation can lead to misguided and non-optimised design solutions, which are pronounced in the design of building envelope [8]. The optimisation can be achieved with the existing energy analysis tolls, but the problem is that building form, orientation and openings are defined in the early design stages, while energy simulations are usually conducted during the final design stages. Consequentially, if energy simulation shows shortcomings, designers are mostly unwilling to make radical changes at the end of the design process and prefer to seek for HVAC solutions, although they are costlier and less energy efficient.

Several building envelope optimisation studies have been published in recent years, focusing on a variety of optimisation factors (e.g. life cycle costs, energy demand, thermal comfort, etc.) [9,10]. In the light of early stages of building design, the most significant influential factors are the ratio between building envelope size and volume (i.e. building form factor), window-to-wall ratio (i.e. WWR) and the use of thermal mass. All of them have substantial influence on the thermal response of a building [6], although the WWR is probably the most pronounced due to the complex impact of solar gains on heating, cooling and lighting energy consumption of a building [25]. Granadeiro et al. [15] state that the building envelope form has significant influence on building energy performance. It is generally thought that when buildings are heating dominated, compact building forms have better energy performance. Although this is to a certain degree true, Premrov et al. [34] have shown that in some cases less compact buildings are more energy efficient. The crucial element of the building envelope, the window, is probably the most important when considering the influence of the envelope on the indoor thermal environment [42] as well as energy consumption of the building. Yu et al. [43] as well as You and Ding [42] demonstrated that an optimum WWR can be determined for a given building, climate and fixed orientation. The optimum WWR is influenced by a multitude of factors, mostly by the climate, orientation and the thermal and optical parameters of the window. This interconnectedness of various influential factors was demonstrated by Ma et al. [28] in the case of 7 locations in the continental USA as well as by

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Echenagucia et al. [10] in the cities of Palermo, Torino, Frankfurt and Oslo. Both studies showed that an optimum window area is highly dependent on the climatic conditions of the building location. Even more influential is the orientation of the windows, as was shown by Echenagucia et al. [10], where the optimum WWR is substantially different for the differently oriented façades. In both studies the optimum size of the window was in the range from 0% to 50%, depending on the orientation and location. It could be argued that these sizes are relatively small, but it has to be stressed that in neither of the studies the influence of window shading was taken into account. Application of shading elements can have a significant influence on the energy consumption of the building, especially in regard to the cooling energy demand [43]. The study conducted by Goia et al. [14] on the impact of shading at different WWR values demonstrated that, similar to the findings of Ma et al. [28] and Echenagucia et al. [10], the optimum is in the range of 35–45%, but with the application of shading this range can be increased to larger WWR values. Differences in the total energy consumption of the building with WWR values between 25% and 65% were shown to be almost negligible. With the use of window shading the situation becomes even more complex, as the type of shading [5] as well as its operating strategy [23,44] can substantially influence the energy balance as well as indoor illuminance conditions.

It has been show by Al-Sanea et al. [2], Zhu et al. [45] and Hudobivnik et al. [17] that, generally, building envelopes with low (i.e. lightweight construction) or excluded building mass (i.e. internally thermally insulated) are underperforming in regard to energy performance when compared to massive building envelopes. Positive influence of building mass on the energy performance of a building was also demonstrated by Andjelković et al. [3], with greater impacts in cases when radiative heating and cooling systems were used. Similarly, Hudobivnik et al. [17] showed substantial positive effects of building mass on passive cooling of buildings in Central European climate. The study conducted by Kitek Kuzman et al. [20] established that the trend in construction industry is moving towards the use of lightweight structures. This means that the existing building models have to be reassessed, because thermal response of lightweight constructions differs from traditional massive buildings [1,16,18]. The question is what role thermal inertia will play in this context. Aste et al. [4] observe that studies report very different estimations on energy saving potential associated with the use of adequate thermal inertia, ranging from a few percentages to more than 80%. On the basis of the analysis performed by the authors for Milan climate [4] it can be concluded that the difference between the heating consumption of a building with low inertia compared to high inertia wall will be in the range of 10%. The difference between the cooling consumption of a building with low inertia compared to high inertia, may reach up to 20%.

Because the majority of studies in regard to energy optimisation of buildings focus on the study of single parameter, more has to be known about the joint influence of the above mentioned factors, especially on the performance of buildings with low thermal mass [17]. Pisello et al. [33] made a study consisting of three different prototypical residential buildings. However, the study is limited only to three specific building geometries. Therefore, a study of influences on a hypothetical, simplified and generic building concerning the envelope orientation, structure and building form in dominant Central European climatic conditions is needed and could be a basis for "rules of thumb" that could be used by building designers in the early stages of design. In the presented paper, we present a parametric study involving dynamic thermal simulation analysis of the impact of building form, orientation and WWR on energy consumption for heating and cooling, executed in a building model situated in a typical Central European climate. Although the presented study is conceptually similar to investigations executed by Olgyay [31] in the 1960ies, it is focused on the performance of buildings with envelope elements corresponding to modern-day legislation and standards. Additionally, the study was concerned with identifying the relative influence of cooling energy use in the Central European climate with different arrangements of building volume, envelope configuration and shading. This interest was fuelled by predictions emphasizing that cooling will become an important issue in the Central European buildings due to climate change [35]. The potential increase of cooling in residential buildings due to climatic changes was clearly illustrated by Pajek and Košir [32] in recently published study, which demonstrated that by 2050 in certain cases buildings in Central European locations could eventually become cooling dominated. Therefore, the insight into general behaviour of generic building models under Central European climatic conditions will represent a valuable resource to building designers at early stages of design. For this reason, this study used building performance simulations, which were carried out by using EnergyPlus [39] software and the Open Studio front end plug-in [30] for the Trimble SketchUp CAD application [37]. The expected results are a set of comprehensive data including the influence of building form, orientation and window size (unshaded and shaded) on the heating and cooling energy consumption of a building.

2. Methodology

The calculations were carried out on a simplified model of a building. The starting geometry of the model building, designated as A0, is cubical without windows. The dimensions are 10 × 10 × 10 m, with the total facade surface of 400 m^2 and roof and ground slab surface of 100 m^2. For the model building we presumed three floors and a total conditioned volume of 1000 m^3. The building was oriented to cardinal points. South orientation was designated as 0°. On the east side there is a door with the dimensions of 1.2 m by 2.1 m.

From the basic square floor plan of the A0 building further four variations with fixed volume but different form were devised. The model buildings designated as A1 and A2 have floor plans in ratios of 1:1.5 and 1:2, respectively. When windows are present in the geometrical model, they are positioned onto the longer façade. The B1 and B2 model buildings have the same shape as the A1 and A2 buildings, but with windows on the shorter façade. This represents the five basic forms of the model buildings, which define the baseline group. To investigate the influence of solar gains, the window area on the south façade was gradually increased in increments from 0%, 25%, and 50% to 100% of the southern façade area. Also the orientation of the buildings was changed in progressive steps of 30° from east through south towards west orientation. In Fig. 1 the principle and the method of generating the above described scenarios are presented. In total, 140 different configurations in the baseline group were calculated. Each case is marked in accordance with its basic simulation parameters (i.e. floor plan shape, window area and orientation). Therefore, for example, A1.25.0° represents a building with a rectangular floor plan in ratio 1:1.5 (A1), 25% (25) of glazing on the longer façade facing south (0°).

Walls were assumed to be composed of aerated concrete blocks with thermal insulation applied on both sides of the construction (16 cm of extruded polystyrene on the external side and 8 cm of mineral wool on the internal side of the wall). The external walls have a U-value of 0.14 $W/m^2 K$. In this way the thermal mass of the walls was in a large part excluded from the "active" part of the building envelope [17]. The floors and roof were assumed to be of traditionally used concrete slabs. The U-value of the roof and ground floor slab was 0.15 $W/m^2 K$. Therefore, the only thermal mass of the building was present in the floor slabs and the roof, which is a similar configuration to the low mass building used in the study of thermal mass impact on energy performance conducted by Andjelković et al. [3].

Another element with significant influence on energy use in buildings is the size and type of windows. Manz and Menti [29] present charts which display condensed information on the energy performance of glazing at eight European locations. By analogy to the studied locations, in the mentioned study triple glazing was chosen with one low-E coating and argon filling (U-value = 1.06 $W/m^2 K$, g factor = 0.58). The influence of window frame was not taken into consideration. The

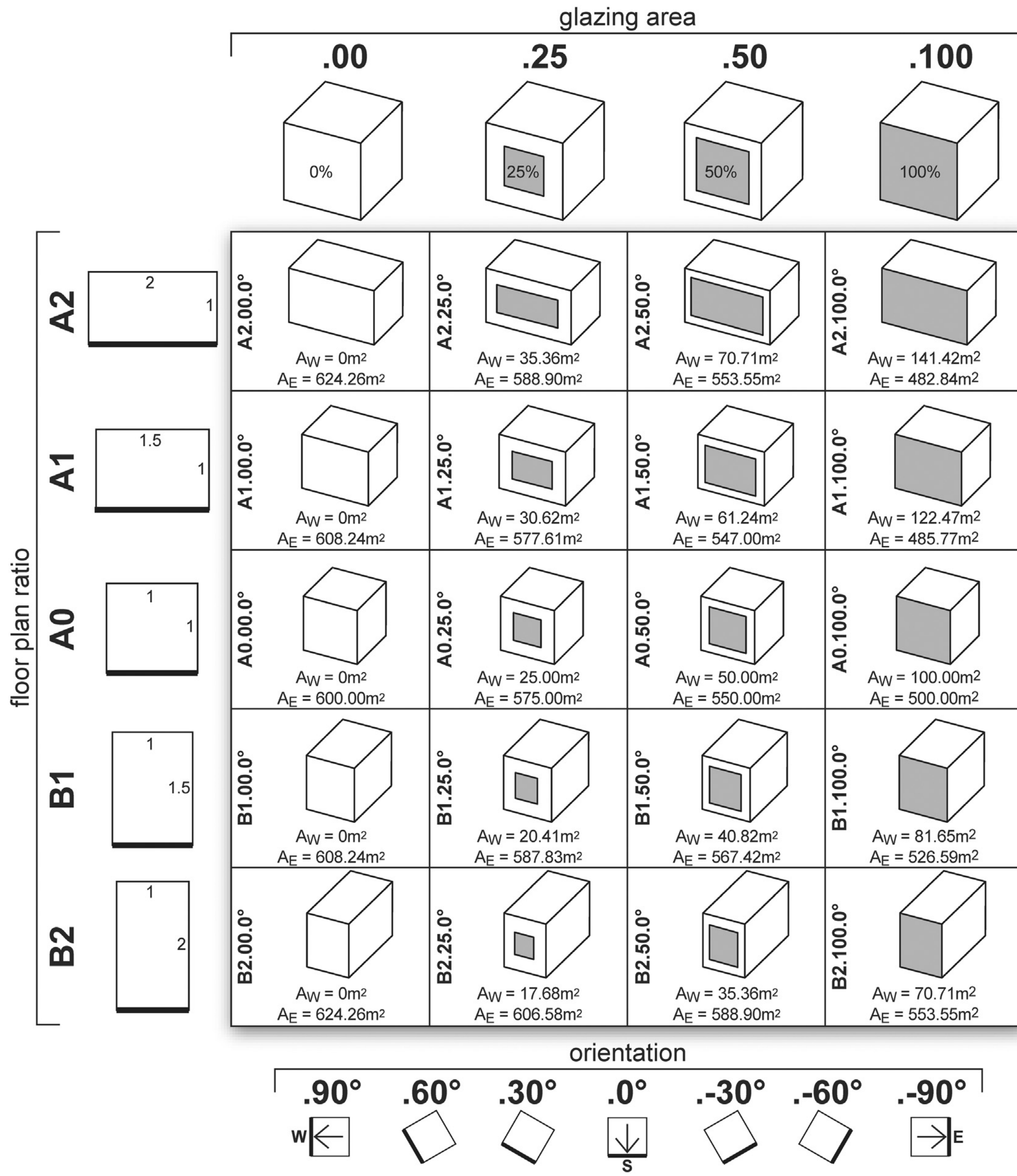

Fig. 1. Methodology applied for the generation of 140 calculated baseline cases. The value of AW represents the glazed surface, while the AE value represents the surface of the opaque part of the building envelope.

door on the eastern façade has the U-value of 1.1 W/m^2 K and is completely opaque. In the baseline group calculations the windows have no shading, because we wanted to establish the influence of solar gains in temperate climate on the heating and cooling energy consumption. This enabled us to determine at which configurations and orientations of the model building shading is needed, and to what extent it influences the energy consumption (especially cooling).

The model building was defined as a single thermal zone, with a heating set-point of 20 °C and a cooling set-point of 26 °C. The HAVC system was idealized and modelled in the EnergyPlus as ideal air loads. Ventilation was modelled as natural with presumed constant air change rate of 0.7 ACH throughout the year. The influence of internal heat gains from occupants and electrical appliances was excluded from the study. It needs to be stressed that this simplification influences the overall energy consumption of the simulated buildings (i.e., generally the cooling energy consumption is lower, while the heating energy is higher). Nonetheless, the influence of internal heat gains was eliminated because the objective of the study was to evaluate the influence of solar radiation in respect to building's form, orientation and glazing area on a generic building type, without the additional influence of space type and consequential occupant patterns and loads.

2.1. Location and climate

Slovenia has a temperate climate, characteristic for the Central, Western and parts of Eastern and Southern Europe [24]. Therefore, Slovenian climate represents the dominant climate type in Europe. In accordance to the Köppen-Geiger climatic classification this climate is classified as warm temperate, humid with warm summers (Cfb class according to the Köppen-Geiger climatic classification [24], which corresponds to ASHRAE 5A climate type [40]). Although the above mentioned climate type is representative for the majority of Europe and therefore also Slovenia, local differences can occur due to a multitude of geomorphological (e.g. influence of mountain ranges and large bodies of water) as well as anthropogenic (e.g. urban heat island) influences. For the simulations in this study a central Slovenian location in the city

Table 1
Climatic data for Ljubljana, Slovenia: average (T_{AVG}), minimum (T_{MIN}) and maximum (T_{MAX}) daily dry bulb temperatures as well as average monthly direct solar irradiation (S_{DIR}).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{MAX}	(°C)	10.0	9.4	16.0	26.0	28.0	30.0	33.4	32.7	27.0	24.2	15.0	10.6
T_{AVG}	(°C)	−1.2	−0.8	3.9	9.4	14.0	16.6	20.4	18.9	14.9	9.6	4.0	0.0
T_{MIN}	(°C)	−13.0	−21.0	−6.0	−0.2	3.0	6.3	10.0	3.0	6.0	−0.6	−5.1	−9.4
S_{DIR}	(W h/m^2)	836	1205	1509	1980	2045	2253	3191	3480	1968	1990	543	267

of Ljubljana was chosen (46°03′N, 14°30′E). According to the EnergyPlus weather file [40] the coldest winter month in Ljubljana is January with an average temperature of −1.2 °C, while the warmest month is July with an average temperature of 20.4 °C, which is comparable to other central European cities. The average daily temperatures and the values of solar irradiation for the location of Ljubljana are presented in Table 1.

2.2. Simulation procedure

The main points of interest in the executed study were the influence of orientation and WWR of the building envelope on transmission losses and solar gains. Solar gains are considered to have a positive and negative effect, depending on the indoor temperature, which results in corresponding heating and/or cooling energy use. On this basis we determined the optimum configuration regarding the cumulative yearly energy consumption. We have to bear in mind that the baseline group variants had no shading, which is why high cooling energy consumption was expected, especially for the configurations with large WWR. Therefore, in additional simulations we tested if the case with the best result regarding heating energy consumption (presumably this variant would be the least successful regarding the cooling energy use), with added external shading devices, could provide the same performance or better than the optimum variant without shading.

The Energy Plus simulations were conducted for the entire year in hourly increments. We chose 6 steps per hour; this means that the simulation software calculated iterations every 10 min. The observed simulation results were the following:

- mean monthly indoor air temperature (T_{IN}) in °C,
- solar (Q_{GS}) and ventilation (Q_{GV}) gains in kWh/m^2,
- transmission losses through glazing (Q_{LW}) and opaque envelope (Q_{LT}) in kWh/m^2,
- ventilation losses (Q_{LV}) in kWh/m^2,
- energy consumption for heating (Q_H) and cooling (Q_T) in kWh/m^2 and
- total annual energy consumption (Q_T) in kWh/m^2.

3. Results and discussion

As the amount of the attained results is too large for the scope of the presented paper, only one case (A0.50.0°) will be described in detail, while all other results will be presented in four groups defined according to the WWR (0%, 25%, 50% and 100%).

3.1. Example of detailed results – case A0.50.0°

The model building of the A0.50.0° case has a square floor plan with dimensions 10 × 10 m and a height of 10 m. The total volume is 1000 m^3, and the surface of the external building envelope is 600 m^2. The southerly oriented façade surface is 50% glazed, which corresponds to 50 m^2 of windows (Fig. 1). The ratio of transparent to opaque façade elements is 12.5%.

The total calculated annual energy consumption for the simulated model building is 76.78 kWh/m^2, of which 91.7% (70.43 kWh/m^2) is for heating (Q_H) and 8.3% (6.35 kWh/m^2) is for cooling (Q_C). Based on the simulation results it is evident that the building is heating dominated, which was expected according to the climatic conditions of the location. Heating is mostly needed from October till April, while cooling is needed mainly in July and August. Energy use for cooling and/or heating is very low during the moths of May, June and October. Total yearly solar heat gains (Q_{GS}) are 56.91 kWh/m^2 with peak gains in August (7.02 kWh/m^2) and the lowest gains in December (1.20 kWh/m^2). Solar gains have a positive effect on the energy balance of the building during the heating season and, of course, a negative effect during the cooling season. The received solar gains from October till April, when the heating energy consumption is the largest, amount to 26.92 kWh/m^2 or 47.3% of the total received solar gains, while during the cooling season of July and August the received solar gains amount to 5.49 kWh/m^2 (9.6% of yearly received solar gains). The remaining solar gains are received during the transitional months, when the energy consumption for cooling and/or heating is low. The ventilation gains are minimal and are present only during the summer months (Table 2). The majority of energy losses of the model building are through ventilation (Q_{LV}) and on the yearly basis amount to 87.27 kWh/m^2 with the highest losses during January and the lowest during July. Compared to the ventilation losses the transmission losses through the building envelope are relatively small, due to the low U-values of the building components, and amount to 34.2 kWh/m^2. Of that, 39% (13.35 kWh/m^2) of energy is lost through the windows and the rest (20.85 kWh/m^2) through the opaque parts of the envelope. It is also worth mentioning that during August the transmission losses through the opaque parts of the envelope are negative, which means that during this time there are even minimal transmission gains present in the building. The results of the A0.50.0° simulations are presented in Table 2.

The average daily mean internal temperatures (T_{IN}) during the year are oscillating between the heating (20 °C) and cooling (26 °C) set-points. The reached temperature is mainly dependent on the balance between ventilation and transmission losses and solar gains. For the presented A0.50.0°case the temperatures during the heating season (October till April) are close to 20 °C, with the highest temperatures

Table 2
Summary of calculated results for the A0.50.0° case.

	Energy consumption (kWh/m^2)		**Gains** (kWh/m^2)		**Losses** (kWh/m^2)		
	Q_H	**Q_C**	**Q_{GV}**	**Q_{GS}**	**Q_{LV}**	**Q_{LW}**	**Q_{LT}**
Jan	15.28	0.00	0.00	3.11	12.93	1.90	3.56
Feb	12.15	0.00	0.00	3.83	11.48	1.59	2.90
Mar	8.81	0.00	0.00	4.87	9.67	1.31	2.70
Apr	4.06	0.01	0.00	5.22	6.38	0.91	1.97
May	0.98	0.05	0.01	5.30	4.39	0.67	1.18
Jun	0.10	0.18	0.04	5.19	3.38	0.54	1.23
Jul	0.00	2.35	0.18	6.40	2.84	0.53	0.85
Aug	0.01	3.14	0.25	7.02	3.66	0.69	−0.21
Sep	0.15	0.49	0.00	6.09	4.27	0.76	0.71
Oct	2.67	0.12	0.00	6.39	6.89	1.15	0.90
Nov	10.61	0.00	0.00	2.30	9.27	1.43	2.20
Dec	15.62	0.00	0.00	1.20	12.11	1.86	2.85
Yearly	**70.43**	**6.35**	**0.48**	**56.91**	**87.27**	**13.35**	**20.85**
Cumulative energy consumption for heating and cooling = 76.78 kWh/m^2							

Table 3
Simulated average mean internal temperatures for the A0.50.0° case.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{IN}	(°C)	20.01	20.05	20.13	20.73	21.60	22.61	25.02	24.81	22.52	21.35	20.05	20.00

reached in October (Table 3). During the cooling season (July and August) the maximum indoor average daily temperature of 25.02 °C is reached during July, which is the hottest month according to the climatic data (Table 1).

3.2. Results for cases with WWR of 0%

The first group of buildings in the baseline cases are buildings without transparent parts. The geometry and the basic characteristics of the model buildings are presented in Fig. 1. These cases do not represent a realistic residential or commercial building but were included in the study in order to enable the evaluation of glazing influence on the energy consumption. Because the model buildings in this group do not have windows, it is expected that the best performing building will be the most compact one, as it has the best ratio between volume and envelope area and therefore the lowest transmission losses. Simulations confirmed the expected results, as the best performing buildings were the A0.00 cases with the heating energy consumption of 94.50 kWh/m^2 per year, while the worst performing ones were the B2.00 cases with the heating energy consumption of 95.29 kWh/m^2 per year. The difference between them is minimal and it only amounts to 0.79 kWh/m^2, i.e. less than 1%. For all simulated building forms, the cooling energy use was zero, as internal temperatures never reached or exceeded the summer set-point of 26 °C. The influence of orientation was marginal, as the difference between the A.0.00.90° and A0.00.-90° cases was only 0.13 kWh/m^2 per year.

3.3. Results for cases with WWR of 25%

The group of model buildings with 25% of glazing is presented in Fig. 1. They are the first group of simulated buildings with windows and therefore represent a realistic building concept. As expected, the simulation results showed that the introduction of windows is reflected in the decrease of Q_H. The lowest heating energy use of 76.62 kWh/m^2 per year is achieved in the A2.25.0° case, which has the largest glazed area of 35.36 m^2. On the other hand, the B2.25.0° case has the smallest glazed area (17.68 m^2) and therefore the largest Q_H of 84.59 kWh/m^2 per year. The difference between the two cases is 7.97 kWh/m^2 or 10.4% (Fig. 2). As expected, the opposite is true for the cooling energy consumption, which is higher in cases with larger window area. The largest Q_C of 3.64 kWh/m^2 per year is reached in the A2.25.-60° case, while the lowest use of 0.47 kWh/m^2 per year is achieved in the B2.25.-90°case. The difference between the worst and the best performing case is 87% or 3.17 kWh/m^2 (Fig. 3). The orientation of glazing plays a crucial role in the final total energy consumption. For heating, as expected, the south oriented cases for all the building types are the best performing. The largest difference in Q_H can be observed in the A2.25 cases with the largest glazed area. The difference between the A2.25.0° and A2.25.-90° cases is 9.21 kWh/m^2 per year, which translates into 12% increase of Q_H. As regards the cooling energy use, a somewhat different correlation between orientation and energy consumption can be observed. The largest Q_C is recorded in cases rotated by 60° from the south orientation, with minor differences between eastern and western oriented cases. Similar as for heating energy, the largest differences are achieved in the cases with the largest glazed area. This trend is accentuated during the cooling season and is the result of the combination of low solar incidence angle and still relatively high solar radiation intensity. The difference between the A2.25.-60° and A2.25.0° cases is 0.79 kWh/m^2 or a decrease of 21.7% in Q_C.

The total energy use is presented in Fig. 4, where it can be seen that the buildings with the largest glazed area (A2.25 cases) are the most efficient only at orientations due south (case A2.25.0°) and for 30° rotation (cases A2.25.30°and A2.25.-30°). Among the 60° rotated cases the A1.25 case buildings become the most energy efficient, while among the 90° rotated cases, the A0.25 cases are the most efficient. The differences are small but, nonetheless, they show that buildings with larger window areas are more energy efficient only if the cooling consumption is relatively low and solar gains during the heating season are high. In the case of buildings with WWR of 25%, this is achieved only at southern orientations where due to favourable solar incidence angles the solar gains during summer are relatively low and are high during winter.

3.4. Results for cases with WWR of 50%

The third group of model buildings are buildings with 50% of glazing installed into the façade (Fig. 1). It was expected that the doubling of the glazed area would result in further reduction of heating energy use but also in the increase of cooling energy use. In the light of the results of the previous group (i.e. WWR of 25%), the main question was whether the buildings with the largest window area would still be the best performing and what influence the rotation of the buildings would have on the total energy consumption.

The lowest Q_H was attained in the A2 building types, which have the largest window area. The heating energy consumption of the A2.50.0° case is 66.62 kWh/m^2 per year (Fig. 2), which is 9.73 kWh/m^2 or 12.7% lower than the energy consumption of the worst performing case of the group B2.50.0° for the south orientation. For Q_C the best performing case is B2.50.90° with annual energy use of 2.87 kWh/m^2, while the worst performing case is A2.50.-60° with 14.83 kWh/m^2 of yearly cooling energy consumption (Fig. 3). The difference between the two cases is 11.96 kWh/m^2 or a reduction of 80.6% in Q_C. The influence of rotation on the heating and cooling energy consumption exhibits similar trends as in the case of buildings with WWR of 25%. The maximums are achieved at −60° rotation, while the minimum energy consumption is achieved at 90° rotation. The trends are similar as in the case of 25% glazed buildings, but with noticeable increase of energy consumption for cooling for buildings with 50% glazing. If we compare buildings with WWR of 25% and 50%, we can see that the A2.50.0° case has by 10.0 kWh/m^2 lower Q_H than the A2.25.0° case. In the mentioned case, the doubling of the glazed area results in 13.05% reduction of Q_H. It is also worth mentioning that the positive effect of larger glazing area is much smaller in east or west oriented cases (Fig. 2), where the difference between A2.50.90° and A2.25.90° is only 5.3%. This is the result of smaller solar gains at these orientations and larger transmission losses through the bigger window area of the 50% glazed group of buildings. The difference in Q_C between the A2.25.-60° and A2.50.-60° cases (i.e. the worst performing cases in both groups) is 11.19 kWh/m^2 or a staggering increase of 307% for the A2.50.-60° case. The B2.25.-90° and B2.50.90° cases have the lowest cooling energy use, where the difference between the two is 2.4 kWh/m^2 per year (Fig. 3).

The Q_T is presented in Fig. 4. From the diagram it is evident that the Q_C is a dominating factor, driving the trend of energy consumption. High cooling energy use translates into the worst cumulative performance of the A2.50 cases, even though they exhibit the lowest heating energy consumption (Fig. 2). The best performing building type is the A0.50.0° case with cumulative energy consumption of 76.78 kWh/m^2 per year. The A0 type buildings are also the best performing cases for

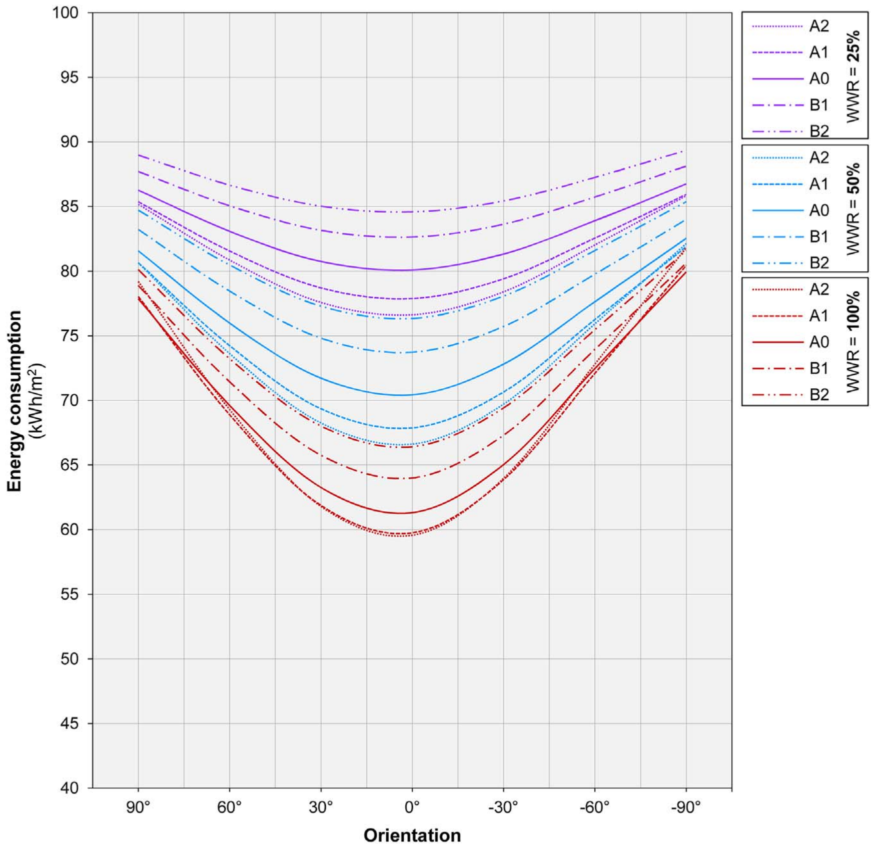

Fig. 2. Simulation results for yearly heating energy consumption in relation to the WWR, floor plan ratio and orientation.

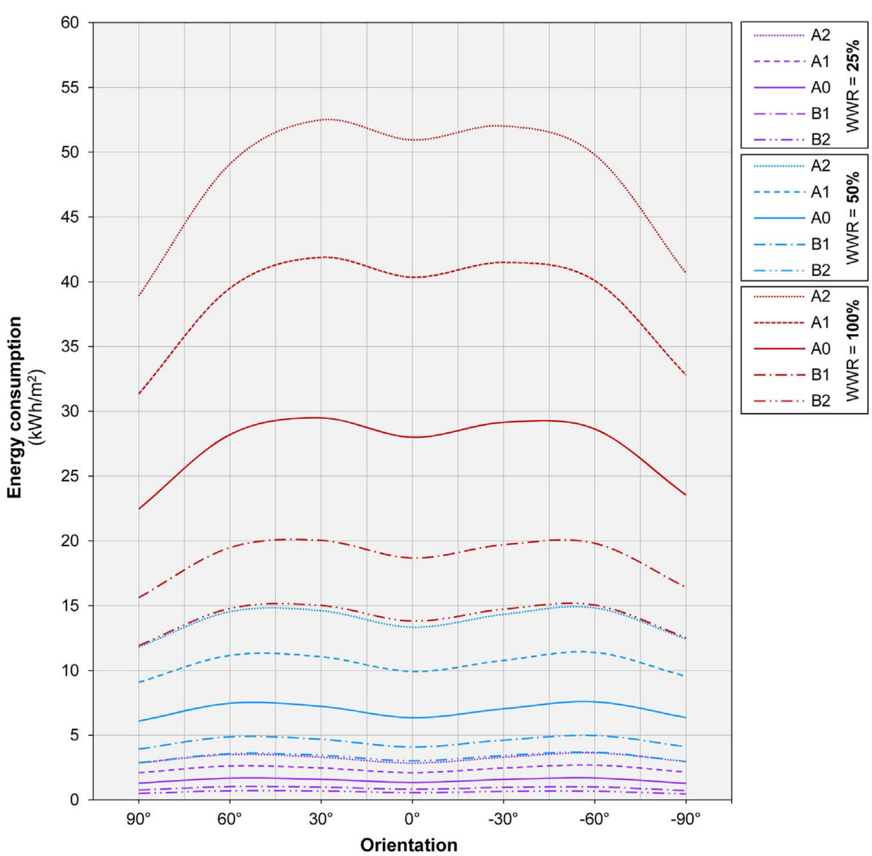

Fig. 3. Simulation results for yearly cooling energy consumption in relation to the WWR, floor plan ratio and orientation.

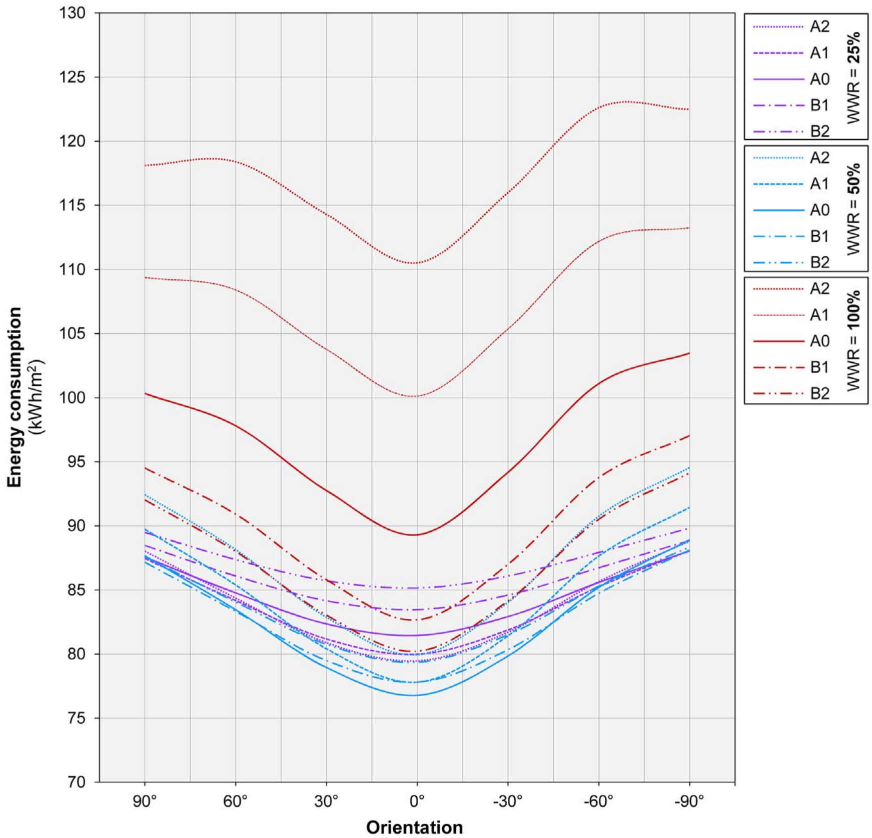

Fig. 4. Cumulative yearly energy consumption in relation to the WWR, floor plan ratio and orientation.

30° and −30° orientations, while for other orientations the B1 type exhibits better results.

3.5. Results for cases with WWR of 100%

The last group of simulated buildings of the baseline cases are buildings with WWR of 100% (Fig. 1). On the basis of the results for the groups of buildings with WWR of 25% and 50% we can expect that the energy use for cooling will become even higher and that the buildings with the largest glazed area will also be the worst performing when cumulative energy consumption is considered.

As in the previous groups, the best performing building type in regard to the Q_H is the A2 type. The A2.100.0° case exhibits 59.57 kWh/m^2 of heating energy consumption per year, which is 6.85 kWh/m^2 (i.e. 10.3%) less than the worst performing case for the south orientation (B2.100.0°). However, it is worth mentioning that this is true only for 0°, 30° and −30° orientations. For 60° and −60° orientations the A1.100 type is better performing, while for east (i.e. −90°) and west (i.e. 90°) orientations the best performing building type is A0.100 (Fig. 2). As expected, the Q_C is the highest for the A2.100 building type, reaching the maximum value of 52.49 kWh/m^2 in the A2.100.30° case. The B2.100.90° case (Fig. 3) exhibits the lowest Q_C of 11.92 kWh/m^2 per year. The difference in cooling consumption between the best (i.e. B2.100.90°) and the worst (i.e. A2.100.30°) performing cases is 40.57 kWh/m^2 or a reduction of 77.3%. From the previous groups of calculated cases it has become evident that the rotation of the buildings has substantial influence on the heating and especially on the cooling use. The same trend continues also in the 100% WWR group of buildings. An important difference is that the maximum Q_C is reached at 30° and −30° orientations (52.49 kWh/m^2 per year for the A2.100.30° case), while in previous groups it was reached at 60° and −60° orientations. The minimum Q_C for all groups is reached at east and west orientations (Fig. 3).

The orientation of buildings also has substantial influence on the Q_H, as the best performing case of the 100% WWR group at orientation 0° (i.e. A2.100.0°) becomes the worst performing case at orientation −90° (i.e. A2.100.-90°). If we compare the results for the Q_H with previous groups, it becomes evident that at 100% WWR larger window areas are advantageous only at south orientations (i.e. 30° through −30°). At orientations further to the east or west, large window area becomes a handicap, because transmission losses through the windows become larger than solar gains. At these orientations the difference between various cases of the 100% WWR group become marginal, as the largest difference (between A0.100.90° and B2.100.90°) is only 2.25 kWh/m^2 (Fig. 2). If we compare the heating energy consumption of the A2.50.0° and A2.100.0° cases, we can see that the doubling of the glazing area reduces the Q_H by 7.05 kWh/m^2 or by 10.6%. On the other hand, the doubling of window area results in an increase of Q_C by 37.26 kWh/m^2 or by 279%.

The Q_T of the 100% WWR group of buildings is presented in Fig. 4. It shows the opposite situation to the cases with smaller WWRs, as the cases with smaller transparent areas (B1.100 and B2.100 types of buildings), are performing better than the buildings with larger window areas (A1.100 and A2.100 types of buildings), irrelevant of the orientation. The worst performing case is A2.100.-60° with the Q_T of 122.62 kWh/m^2, while the best performing case is B2.100.0° with the Q_T of 80.22 kWh/m^2. The difference between the two cases is 42.4 kWh/m^2, which is the largest difference between the best and the worst performing case of all the groups. The A2.100.-90° case is also the worst performing case of all the 140 baseline cases (Figs. 4 and 6). Results of the conducted simulations for all forms and WWR values at south and east orientations are presented in tabular form in Figs. 5 and 6. In addition to the Q_H, Q_C and Q_T values in kWh/m^2 per year, figures also present relative differences between baseline cases with A0.50.0° (i.e. best performing case) as a reference (shaded cell in Fig. 5). The results show that at 50% WWR and south orientation the difference in Q_T between different floor plan shapes is marginal. At such WWR, all of the calculated cases are within 4% points from the best performing

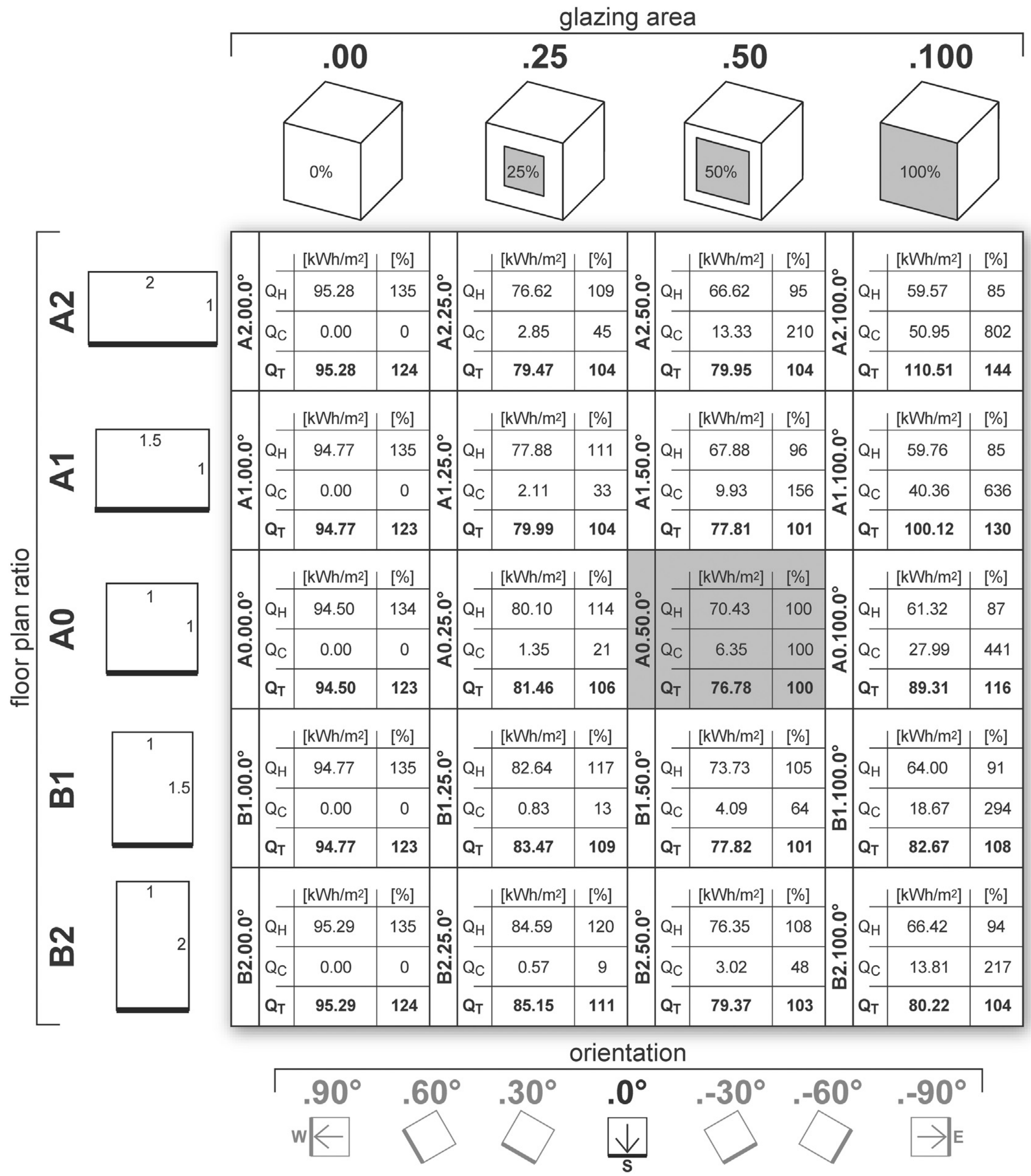

Fig. 5. Results for Q_H, Q_C and Q_T for the south (0°) oriented cases of the baseline group. Relative values are calculated with A0.50.0° case as reference (shaded cell).

case. The difference becomes more pronounced at l00% WWR. Here due to the substantial increase in Q_C the difference in Q_T between A0.50.0° and A2.100.0° amounts to 44% points (Fig. 5). Orientation also plays an important role, as the increase in Q_T between the best performing south oriented case and all east oriented cases is between 15 (i.e. A1.25.-90°) and 60 (i.e. A2.100.-90°) percentage points (Fig. 6).

3.6. Influence of shading

According to the performed simulations, the lowest Q_T of 76.78 kWh/m^2 per year was achieved in the A0.50.0° case (Fig. 5). This case has a compact building form with middle sized window area (50 m^2). As it can be seen from Fig. 7, the cases with the lowest heating energy use also exhibit the highest cooling energy consumption (e.g. A2.100.0°). Of course, none of the baseline cases had any shading applied to the transparent parts of the building envelope. On the basis of previous studies [43,14] we can assume that window shading during the cooling season will have a significant effect on the cooling energy consumption. A building with substantial window area and appropriate shading (e.g. A2.100.0° and A1.100.0° cases) might, therefore, be more efficient than the A0.50.0° case.

We tested the influence of shading on cumulative energy consumption of three buildings: A1.100.0° (Q_T = 100.12 kWh/m^2), A2.100.0° (Q_T = 110.30 kWh/m^2) and A0.50.0° (Q_T = 76.78 kWh/m^2). The latter was included as a reference case, because it was the best performing building of all the baseline cases (Fig. 5). In the first step of the calculations we used overhangs mounted above the windows in each floor. We expected the elements to be relatively effective at south orientations, as they would block most of the incoming solar radiation during summer, while during winter they would have little effect on the received solar gains. In order to define the optimum length of the overhangs, we performed calculations on the A1.100.0° case, where we increased the length of the overhang in 0.25 m increments and observed the effect on the heating, cooling and cumulative energy consumption of the building. At the optimum length of the overhang (1.75 m) the cumulative energy consumption was 81.10 kWh/m^2 per year or a reduction of 19% (i.e. 19.02 kWh/m^2) in comparison to the unshaded case. The cooling energy use was reduced by 32.03 kWh/m^2

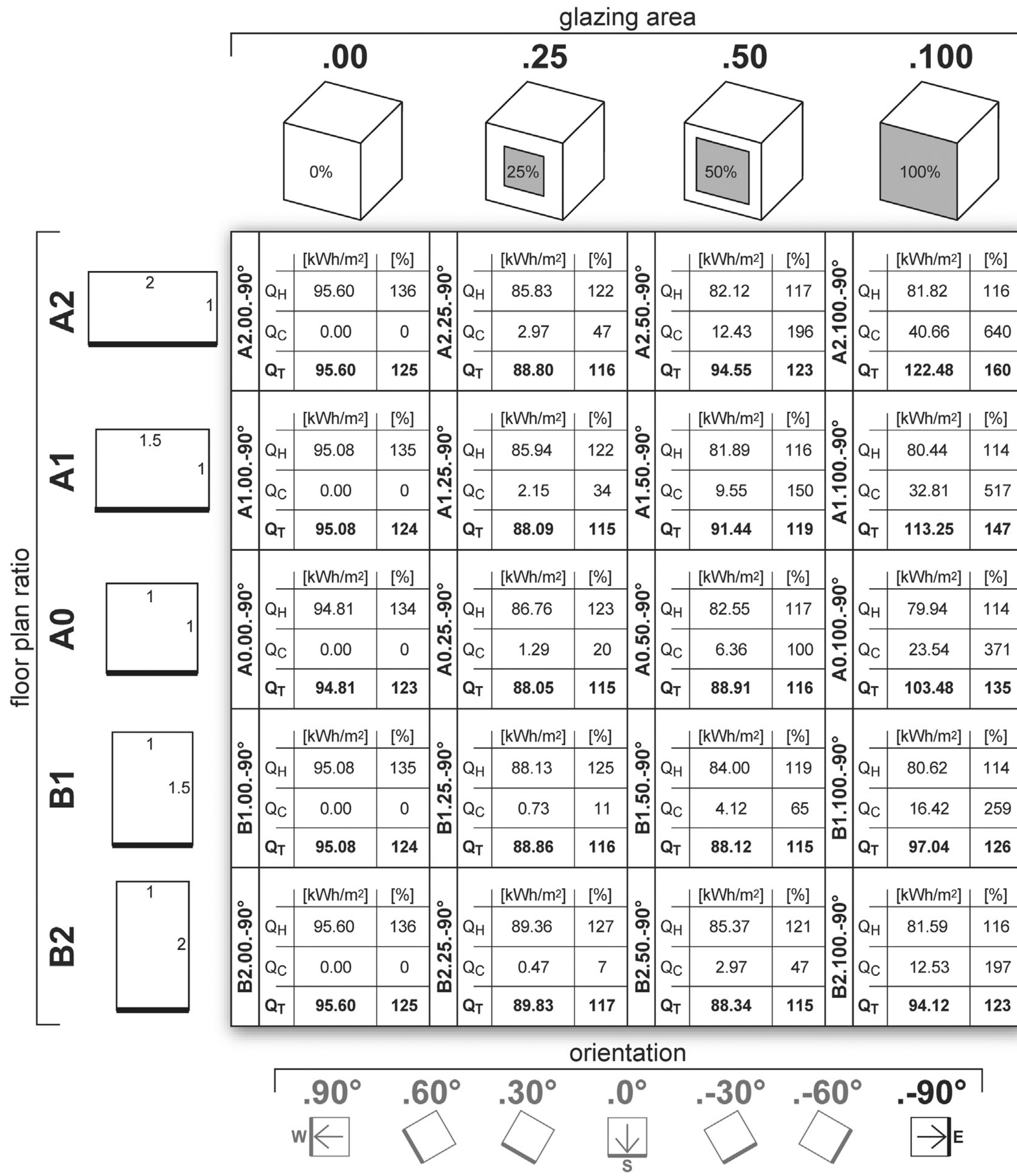

Fig. 6. Results for Q_H, Q_C and Q_T for the east (−90°) oriented cases of the baseline group. Relative values are calculated with A0.50.0° case as reference (shaded cell in Fig. 5).

(reduction by 79.4%), while the heating energy use was increased by 13.01 kWh/m^2 (increase of 21.8%). For the A2.100.0° building the same length of the overhang was used because both model buildings have the same window height. The cumulative energy consumption for the shaded A2.100.0° case was 84.15 kWh/m^2 per year. Reduction of 23.7% (i.e. 26.15 kWh/m^2) was achieved in comparison to the same unshaded model building. The cooling energy consumption was reduced by 78.3% (i.e. 39.66 kWh/m^2) and the heating energy use was increased by 22.6% (i.e. 13.51 kWh/m^2). From the above results it can be seen that the use of shading drastically reduces the cooling energy consumption, while at the same time it also somewhat increases the heating energy use. Nonetheless, cumulative energy consumption results presented in Fig. 7 show that shading substantially decreases the energy consumption in both cases. Q_T was also calculated for the shaded A0.50.0° case. Because the window area is smaller, shorter overhangs (1.25 m) produce optimum results. The cumulative energy consumption increases by 2.3% (1.77 kWh/m^2), compared to the same unshaded case (Fig. 7). Therefore, the use of this type of fixed shading is not appropriate in the instance of the A0.50.0° case.

On the basis of the above described results we executed three additional calculations with removable overhangs used only during the cooling season (from 15th of May till 15th of October). The simulation results showed additional benefits, as the negative influence of shading during heating season was almost eliminated, while all the positive effects during the cooling season remained. With movable shading the Q_T of the A2.100.0° case is 77.32 kWh/m^2, which is negligible 0.7% more than for the unshaded A0.50.0° case. For the A1.100.0° case the results are even better, as the Q_T amounts to 73.29 kWh/m^2 per year, which is in fact the best recorded result of all the calculated cases.

4. Conclusion

In the presented study the influence of building form, orientation and window area on energy consumption in temperate Central European climate was considered. Dynamic analysis of energy consumption in buildings was conducted for three groups of baseline cases, one with cubical form (A0) and two with elongated building forms (A1 and A2), and various portions of glazing. In current European building

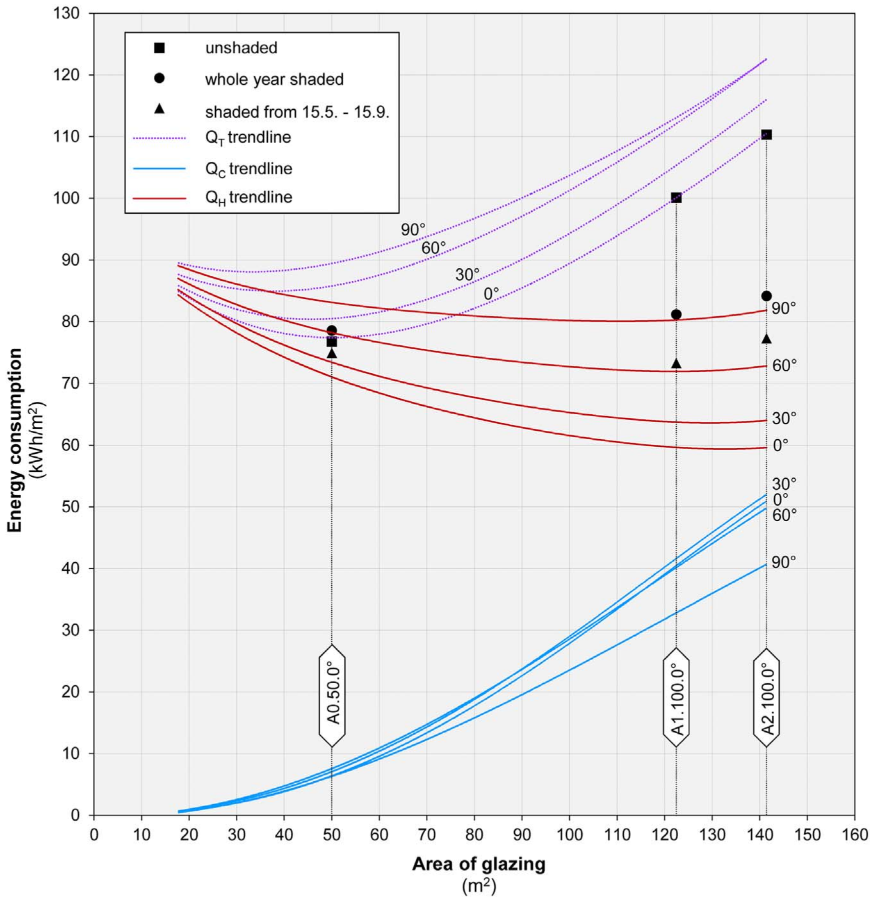

Fig. 7. Trend lines for Q_H, Q_C and Q_T based on 140 calculated cases. Additionally, the influence of shading on Q_T of the A0.50.0°, A1.100.0° and A2.100.0° cases is depicted.

practice, it is generally assumed that compact building forms with moderate portion of glazing and predominantly heating oriented design features achieve the best energy performance. However, there exists doubt that such approach is appropriate for all building designs, in particular for lightweight construction with moderate or low thermal mass, as was demonstrated by Premrov et al. [34] and also by this study.

Major conclusions drawn on the basis of the executed simulations:

If a building has no glazing, energy consumption depends only on the building form factor. In other words, the most compact building (e.g. cube) has the lowest energy consumption. But we have to put this statement into context, because if the building envelope is well insulated, as it was in our case, the difference between the cubical and the elongated shape is quite small (less than 1%, see Figs. 5 and 6). Therefore, less compact building form does not cause any significant increase in energy consumption. This is important information, as less compact buildings enable better access to solar radiation and daylight.

As expected, the introduction of windows results in the decrease of energy consumption. This trend, of course, is not linear and increasing the window area to extremes does not result in lower heating energy demand. For the studied cases an optimum (without shading) is reached at around 130 m^2 of glazing (100% glazed facade) at south orientation (i.e. 0°). At other orientations optimums are reached at lower portion of the glazed area (Fig. 7). Therefore, a building with elongated form (e.g. the A1 and A2 cases) performs better, because the area of glazing on the south façade can be larger than in the case of a more compact building form (e.g. the A0 cases).

In regard to the cooling energy consumption the opposite is true, as the increase of glazed area results in the increase of cooling energy demand. The cooling energy demand is negligible at lower portions of glazing (e.g. at 20 m^2), but it becomes a decisive factor at larger portions (e.g. at 130 m^2), where the cooling energy demand is almost equal to the heating energy demand (Figs. 5 and 7).

The influence of window orientation is very important for heating energy consumption. As it can be seen from Figs. 5–7, the difference between the optimum cases for east or west oriented windows (i.e. 90°, −90°) and the south oriented one is in the range of 20 kWh/m^2 per year (i.e. 25% difference between the two cases). In the case of cooling energy consumption the orientation is less important. The Q_C for window orientations 0°, 30°/−30° and 60°/−60° is almost identical (Fig. 7).

It was found out that the most energy efficient case without window shading was the A0.50.0° case with WWR of 50%. This is more than was determined by Ma et al. [28] and Echenagucia et al. [10] in their studies. However, one significant difference between the mentioned two studies and this study is that we applied glazing only on one façade, while both of the mentioned studies had glazing on all four sides of the building. We presumed that window shading during the cooling season would further reduce the cooling energy consumption. Fixed shading reduced cumulative energy consumption of the unshaded A1.100.0° case by 19% (i.e. 18.95 kWh/m^2 per year). With removable shading the cumulative energy consumption was decreased by 27% (i.e. 26.83 kWh/m^2 per year), while the cooling energy was reduced by 75% (i.e. 30.33 kWh/m^2 per year). These conclusions are similar to the findings by Goia et al. [14]. As expected, the reduction of cumulative energy consumption is more significant in the case of larger glazing portions and in the case of removable shading, therefore indicating the importance of proper shading control [22,23,44,7].

The study showed that elongated building form in Central European climate is more favourable, because it allows large south oriented window areas and thus efficient harvesting of solar energy. This is in line with the findings of Caruso et al. [7], which demonstrated that building form has a decisive influence on energy efficiency in heating as well as in cooling dominated locations. With the application of shading, especially movable shading, minimal energy consumption is achieved at even larger window areas. In such cases proper application and control of movable shading devices becomes crucial due to its influence on cooling, heating and daylighting [38]. The results can be used as design guidelines in early stages of building design without the need for time consuming energy simulations, therefore potentially reducing the end energy use of buildings as well as promoting passive solar architecture measures. For specific building cases the urban morphology has to be taken into account, as it was show by numerous studies that its influence on the energy balance of the building as well as on the daylighting can be substantial [19,21,27,36].

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